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## Wireless communication with miniaturized sensor devices in swimming

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### Abstract

Assessing the performance of athletes is an on-going research topic. In this paper, research has been conducted towards the monitoring of swimming motion using accelerometers and gyroscopes and towards the transmission of this data in real-time to the poolside in a wireless sensor network. Wearable systems provide several advantages compared to the more commonly used video capturing methods. However, challenges remain in the miniaturisation, wearability and robustness of these systems. Also the wireless communication in the aquatic environment presents significant challenges. Higher carrier frequencies lead to a higher attenuation effect due to the water and lower frequencies lead to a lower comfort due to increasing antenna size, hence presenting a trade-off. This paper presents a new miniaturized sensor system that is able to measure the tri-axial angular velocity and acceleration of a swimmer with an on-board transceiver at 433MHz and an on-board memory for data logging.

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## 1. Introduction

This research builds on the need of technology supported exercising which can be found in many other sports (e.g. cycling & running). Nowadays in swimming, most of the coaching occurs by using only a stopwatch to measure split times or stroke frequencies of athletes. However, this imposes restrictions in the amount of athletes that can be followed up and adjusted by the coach. The purpose of this research is to design a system that automatically registers parameters such as stroke type, lap time, lap count, stroke frequency and distance per stroke in order to be able to quantify the performance of an athlete during a workout or to track his performance for an entire season. By quantifying the performance of an athlete during workouts, the training periodization or the training focus could be adapted based on the gathered information to achieve an improved personalised training program in the preparation phase towards an important competition or goal. Dekerle (2006), Nomura et al. (2002) and Alberty et al. (2009) have shown that swimming parameters give an indication of training intensity and may therefore possibly also be used to steer the physiological load more specifically during a workout. Our system is designed for daily use in practice sessions. It is our goal to design a system, which is independent of infrastructure and as such is deployable anywhere at any time. Also, the device renders the installation of further equipment in the pool environment obsolete, whence it achieves an improved ease of use in a short setup time. The aim of our research is to support wireless online as well as offline registration of the movement of a swimmer. The rationale is that the system has to be applicable for a broad public on a daily basis, i.e. without the necessary presence of a coach.

In 2002, Ohgi stated that most of the currently used evaluation methods in swimming involve video systems to record the movements of the athlete. Video systems offer the advantage of providing easily, qualitatively interpretable data, but often do not quantify any parameters in an automated way according to Mayagoitia (2002). Some systems use computer vision techniques as in Abdel-Aziz (1971) to quantify swimmer's positions but experience obstruction by bubbles. These video systems cannot be used in a practice environment with multiple swimmers in the water, evidently because it is not possible to make a recording of every swimmer individually without an extensive camera system. Another disadvantage of these systems is the restriction some public pools impose concerning filming in order to safeguard the privacy of their customers. As our goal was to design a system that can be used during every practice in any pool, video based systems were eliminated as an option.

Contrary to video systems, cable systems are able to easily extract parameters automatically, as was shown in Craig et al. (1979), Craig et al. (1985) and Craig et al. (2006). Cable systems consist of attaching the swimmer to a pulley. During swimming the rotation of the pulley is measured, providing the possibility to obtain the position and speed of the swimmer. Craig et al. combined the measured signal with a video registration to make the data easily interpretable. Although this system is able to automatically provide the swimmer and coach with parameters, it cannot be used in a daily practice context. The use of cables is not user friendly and impossible to apply in a situation with multiple swimmers in one pool lane and is therefore not adopted here.

The presented device is based on accelerometer and gyroscope measurements. Due to the emergence of MEMS technology and the accompanying price drop, accelerometers are nowadays a common choice in several applications to quantify movement, Verplaetse (1996). The possibility to register several parameters using a tri-axial accelerometer in swimming was already explored in Pansiot et al. (2010), Bächlin et al. (2009) Davey et al. (2008), James et al. (2004) and Davey et al. (2004). The systems were placed on the head, back, wrist or the sacrum and were able to measure time per stroke, stroke frequency and lap times offline. The systems were sometimes able to distinguish some or all swimming strokes. The roll- and pitch-angles could be calculated from the acceleration data. Other research by Ohgi (2002) was focused on measuring several phases within a freestyle arm pull by attaching a system to the wrist. Ohgi (2005) was also able to assess fatigue. Research by Le Sage et al. (2010) and Slawson et al. (2010) has also been conducted in providing online measurements. However, no system was developed which supported online and offline movement registration of the swimmer aiming for a comfortable wearability.

## 2. Design

A miniaturized system has been designed ( $16 \times 12 \times 10 \text{ mm}^3$ ) containing a flash memory, accelerometer, gyroscope, microcontroller, battery and transceiver. A block diagram of the system is illustrated in Fig. 1. The accelerometer and gyroscope are sampled on three orthogonal axes at 100Hz within a respective range of  $\pm 2\text{g}$  and  $\pm 250^\circ/\text{s}$  at a resolution of 16 bits in order to accurately register the motion of the athlete. In the MPU-6000 [Invensense], both sensors are integrated in a single package and share the digital interface, which reduces size. A NOR flash memory N25Q064A13EF640E [Micron] with a capacity of 64Mb was selected. The system can therefore register the aforementioned motion data for 116 minutes, which is ample for registering data during our preliminary tests. Communication between digital blocks uses the Serial Peripheral Interface protocol (SPI).

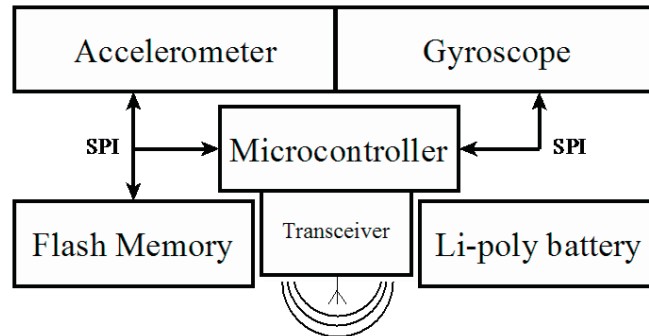


Fig. 1. Block diagram of the system

To provide the system with power for the duration of our test runs, a small 3.7V lithium-polymer battery ( $16 \times 12 \times 5 \text{ mm}^3$ ) with a capacity of 40mAh is included into the system, contributing only to half of the system's size. To achieve our primary concern of low power consumption, we programmed a CC430F5135 [Texas Instruments] microcontroller with dedicated, application specific, interrupt-driven software. This microcontroller was chosen because it embeds an RF transmission stage, which reduces the overall size and power consumption. The RF communication was fixed at the 433MHz ISM-band, as a compromise in the trade-off between data rate, antenna size and increasing water attenuation with increasing carrier frequency. To fulfil the miniaturization requirement surface mounted components are selected. These components were laid out on a double layer printed circuit board (PCB) with a strong focus on system miniaturisation. A programming interface is implemented in the PCB design to facilitate reprogramming and debugging of the microcontroller code. Also a universal asynchronous receiver/transmitter (UART) interface is included in the design. In this way, it is possible to read out data from the device through a virtual serial port on a personal computing device.

The design of our system is smaller than any of the existing systems, which makes it ideal for wearable application in swimming, as swimming athletes are very demanding with respect to comfort. Big bulky devices hinder the athlete and create a specific and different proprioceptive awareness in the water, which is unfavourable because a workout should always try to closely simulate the competition situation. It can be stated that the size of the device does not influence the training process nor the biomechanical environment of the swimmer.

## 3. Experiments

To test the functionality of the system in an initial phase, the system was not yet packaged into its final housing, as this would inhibit further modifications to the electronic circuits and embedded program if considered necessary in this stage. Instead, a waterproof mobile phone case [Aquapac] was used to keep the system waterproof in our initial tests. Fig. 2 (a) demonstrates the setup of our initial tests

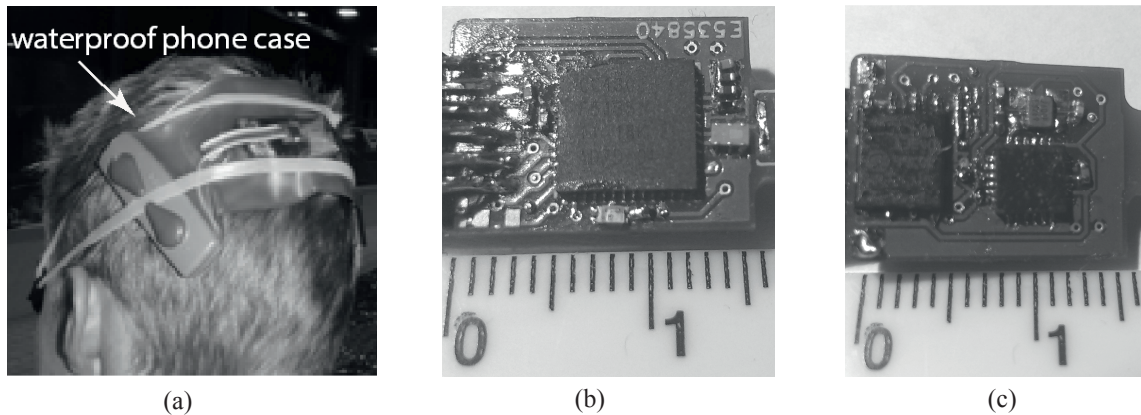


Fig. 2. (a) Measurement setup as part of the goggle straps (b) System top view (c) System bottom view

Tri-axial accelerometer and gyroscope data was collected and stored on the on-board flash memory. A test run consisted of a 200m individual medley (IM), because it contains all four official swimming stroke types (butterfly, backstroke, breaststroke and freestyle). Test subjects were asked to adapt breathing patterns in butterfly by breathing every two strokes the first 25m, and every stroke the second; and in freestyle every two during the first length and every three strokes in the second length of the pool. The three orthogonal accelerations ( $a_x$ ,  $a_y$ ,  $a_z$ ) and angular velocity components ( $\omega_x$ ,  $\omega_y$ ,  $\omega_z$ ) were filtered using a moving average filter with a size of 20 samples. Fig. 3 shows this filtered 200m IM data with the module mounted on the head.

### 200 m Individual Medley (25 m pool)

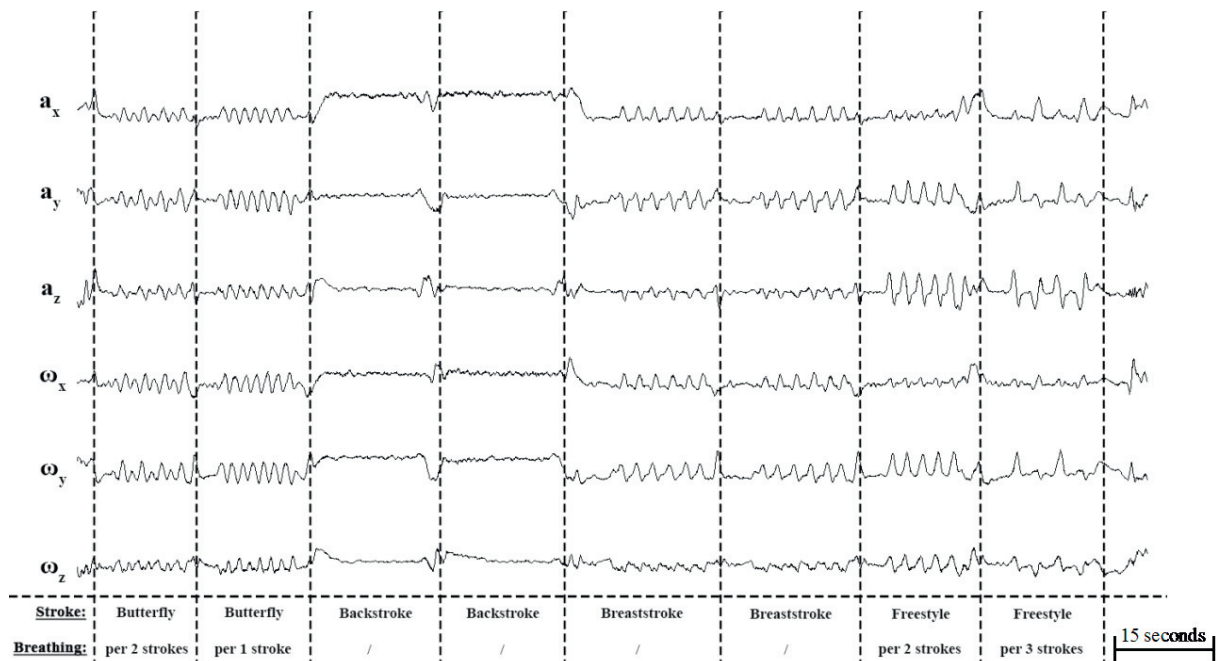


Fig. 3. Measured data after filtering of a 200m individual medley in a 25m pool (15 seconds for scale)

Data was transferred from the on-board flash memory over UART and a virtual COM port to a personal computing device using MATLAB [MathWorks] and stored for further analysis. The four separate strokes are clearly distinguishable and so are wall turns and breathing patterns. This makes it possible to extract parameters such as split times, breathing rhythms, stroke types and the time underwater after push-off from the wall. Fig. 4. shows an analysis of the breathing rhythms in a 25m breaststroke with indication of breathing phases (\*) and gliding phases (~) in one of the accelerometer's axes.

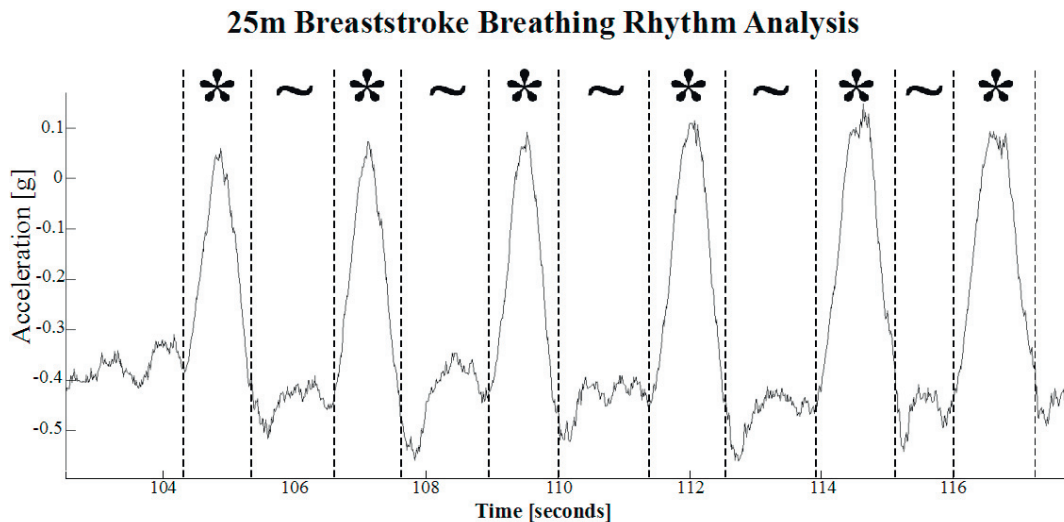


Fig. 4. 25m breaststroke breathing rhythm analysis on x-axis acceleration (\* = breathing phase, ~ = gliding phase)

#### 4. Conclusions and future work

Our current system successfully collects raw accelerometer and gyroscope data of all four swimming strokes with a minimum sized device. By extracting only the important and relevant information, the amount of data can drastically be reduced, which has direct implications on the wireless communication throughput, memory and power requirements. In collaboration with the Flemish swimming federation, as much useful parameters as possible will be extracted from the inertial sensor data. Primary parameters of focus are: split times, stroke frequencies, breathing patterns and distance per stroke. In the development of these data processing algorithms, the implementation into a low-power microprocessor will be taken into consideration. The algorithms will therefore have to be lightweight, fast and consume a minimal amount of power. Possibly, during some parts of the trajectory, the accelerometer and/or gyroscope may be switched off or can be more intelligently sampled at a variable rate.

Our developed device is currently being used to collect motion data at several locations on the body (i.e. head, wrist, sacrum) in comparison to visual data captured by video. By exploiting the on-board transceiver for real-time transmission of this data using a 433MHz communication link, and logging of motion and wireless link quality on the memory, the phases of the swimming stroke where robust wireless communication is possible are expected to become clear. Research is being conducted into the design of an on-body wearable and comfortable antenna at 433MHz.

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## References

- Dekerle, J., 2006. 'The use of critical stroke velocity in swimming? A place for critical stroke rate?', Xth International Symposium on Biomechanics and Medicine in Swimming, University of Porto, Porto, pp.201-205.
- Nomura T., Shimoyama Y., 2002. "The relationship between stroke parameters and physiological responses at the various swim speeds". In: Chatard JC (ed.), *Biomechanics and medicine in swimming IX*. Saint Etienne: publications de l'Université de Saint Étienne, pp. 355- 360.
- Alberty, M., Sidney, M., Pelayo, P. & Toussaint, H. M., 2009. 'Stroking characteristics during time to exhaustion tests.', *Med Sci Sports Exerc* 41(3), 637--644.
- Ohgi, Y., 2002. Microcomputer-based acceleration sensor device for sports biomechanics -stroke evaluation by using swimmer's wrist acceleration, in 'Proc. IEEE Sensors', pp. 699--704.
- Mayagoitia, R. E., Nene, A. V. & Veltink, P. H. 2002. 'Accelerometer and rate gyroscope measurement of kinematics: an inexpensive alternative to optical motion analysis systems', *Journal of Biomechanics* 35(4), 537 - 542.
- Abdel-Aziz, Y. & Karara, H. 1971. Direct linear transformation from comparator coordinates into object space coordinates in close- range photogrammetry., in 'Proceedings of the Symposium on Close- Range Photogrammetry', pp. 1-18.
- Craig, A. B., Skehan, P. L., Pawelczyk, J. A. & Boomer, W. L., 1985. 'Velocity, stroke rate, and distance per stroke during elite swimming competition.', *Med Sci Sports Exerc* 17(6), 625--634.
- Craig, A. B. & Pendergast, D. R. 1979. 'Relationships of stroke rate, distance per stroke, and velocity in competitive swimming.', *Med Sci Sports* 11(3), 278--283.
- Craig, A. B., Termin, B. & Pendergast, D. R. 2006. 'Simultaneous Recordings of Velocity and Video During Swimming', *Portuguese Journal of Sport Sciences* 6: supl. 2, 32-35.
- Verplaetse, C. 1996. 'Inertial proprioceptive devices: self-motion- sensing toys and tools', *IBM Syst. J.* 35(3-4), 639--650.
- Pansiot, J., Lo, B. & Yang, G.-Z. 2010. Swimming Stroke Kinematic Analysis with BSN, in 'Proceedings of the IEEE International Conference on Body Sensor Networks (BSN)', pp. 153--158.
- Bächlin, M., Förster, K. & Tröster, G., 2009. SwimMaster: a wearable assistant for swimmer, in 'UbiComp '09: Proceedings of the 11th international conference on Ubiquitous computing', ACM, New York, NY, USA, pp. 215--224.
- Davey, N., Anderson, M. & James, D. A., 2008. 'Validation trial of an accelerometer-based sensor platform for swimming', *Sports Technology* 1, 202 - 207.
- James, D. A., Davey, N. & Rice, T., 2004. An accelerometer based sensor platform for insitu elite athlete performance analysis, in 'Proc. IEEE Sensors', pp. 1373--1376.
- Davey, N., 2004. 'Acquisition and Analysis of Aquatic Stroke Data from an Accelerometer Based System.', Thesis, Griffith University.
- Ohgi, Y., 2005. Mems sensor application for the motion analysis in sports science, in 'Proceedings of COBEM 2005'.
- Le Sage, T., Bindel, A., Conway, P., Justham, L., Slawson, S. & West, A., 2010. 'Development of a real time system for monitoring of swimming performance', *Procedia Engineering* 2(2), 2707 - 2712.
- Slawson, S., Conway, P., Justham, L., LeSage, T. & West, A., 2010. 'Dynamic signature for tumble turn performance in swimming', *Procedia Engineering* 2(2), 3391 - 3396.